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Effects of Vegetation and Battlefield Obscurants on Point-to-Point Transmission in the Lower Millimeter Wave Region (30-60GHz)

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1. Introduction

The Center for Communication Systems of the US Army Communications-Electronics Command is developing mm-wave radio systems for tactical and strategic communication/data transmission. These systems are designed to operate in the frequency bands of 35-39GHz and 54-58GHz. It is well known that atmospheric effects, battlefield obscurants, and vegetation affect transmission in the lower mm-wave region much less than they affect transmission in the optical range (laser beams). But in order to define performance standards and equipment specifications for mm-wave radios, a data base on propagation effects for this frequency region needs to be established.

The effects of atmospheric absorption, rain, and fog have been studied previously [1], [2]; snow effects on mm-wave propagation are presently investigated in the SNOW 1 and 1A experiments. This paper reports on recent studies on mm-wave transmission through vegetation and through battlefield obscurants such as smoke, dust and artillery shell detonation clouds.

The vegetation experiments [3] were conducted at three frequencies simultaneously, i.e., at 9.6, 28.8 and 57.6 GHz, using special test instrumentation available at ITS, Boulder, CO. They involved measurements over propagation paths through coniferous and deciduous groves, where in the latter case, the tests were repeated under summer and winter conditions; further test runs investigated the effects of dry, wet and windy weather conditions on foliage penetration.

The effects of battlefield obscurants on mm-wave propagation conditions were studied with available mm-wave radios operating in the 38 and 60 GHz bands [4]. Experiments at Grafenwoehr, FRG, were concerned with propagation through smoke and dust, while test runs at Ft. Polk, LA, investigated airborne dust and debris effects produced by artillery shell detonations (DIRT III).

The experiments were complemented by theoretical studies to establish parameter dependencies and assist in the interpretation of measured data. The results of the investigation shows that mm-wave links are capable of providing reliable communication/data transmission in the battlefield environment.

2. Vegetation Experiments

The instrumentation for the measurement program is shown in Figure 1. Both transmitting and receiving terminals are mounted in four-wheel-drive vans for mobility in rough terrain. The RF components are supported on erectable track-mounted carriages to permit ready adjustment of height above ground. In addition, the transmitter mounting permits two meters of horizontal travel to allow variability along this coordinate.

The directional antennas are scaned in elevation and azimuth by a remote-controlled positioner at the receiver terminal to provide data on the intensity of off-angle scatter from foliage and ground reflection effects.

Three frequencies, 9.6, 28.8, and 57.6 GHz, are used simultaneously to obtain frequency dependent data to aid in developing transmission loss models for specific types of vegetation. Both vertical and horizontal antenna polarization are mechanically selectable at each terminal which permits measurements for each case, including cross polarization. Beamwidths of the transmitting antennas are 10^{o} at all frequencies. Receiving antenna beamwidths are 4.8^{o} at the 9.6 GHz frequency and 1.2^{o} at 28.8 and 57.6 GHz. A 70 dB dynamic range and a minimum sensitivity of -100 dBm is available at all frequencies.

The data recorded from these measurements consists of received signal amplitudes from both azimuthal and elevation scans at transmitter and receiver heights from 1 to 9 meters above ground. The transmitter antennas were normally fixed at a zero angle (on-path) pointing and the receiving antennas were scanned at $\pm 20^{o}$ in the azimuthal plane and $\pm 15^{o}$ in the elevation plane. In most test, the transmit and receive antennas were positioned at the same height above ground.

The significant results and observations from this study are listed in the following summary statements with specific illustrations shown in

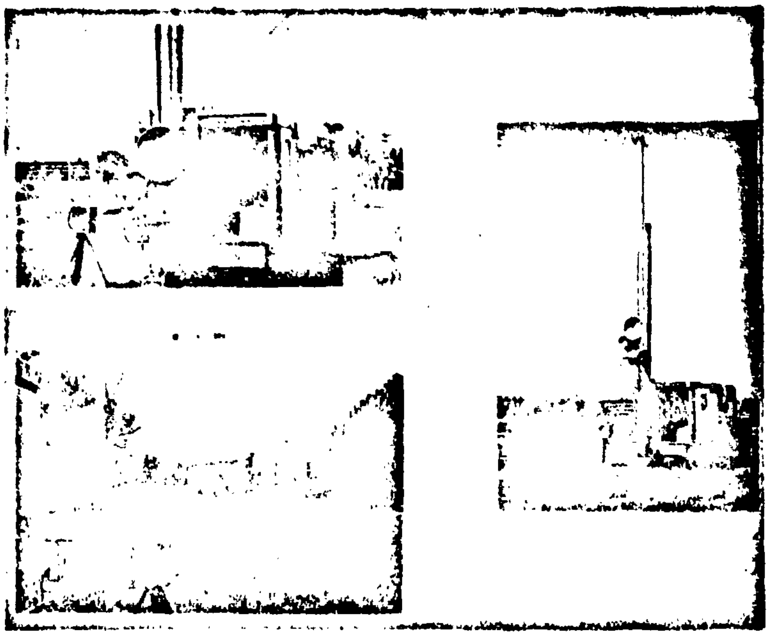

Fig. 1. Transmitting and receiving equipment used for the vegetation measurements.

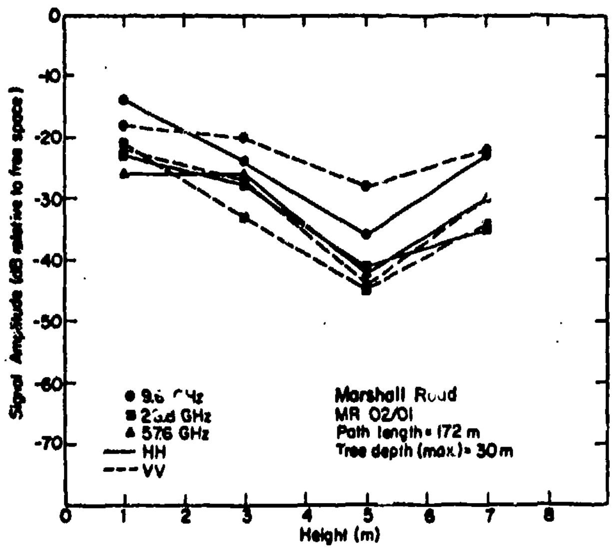

Fig. 2. Signal amplitude as a function of height for a cottonwood grove (HH polarization and VV polarization).

Figures 2 through 5:

a. The measured signal loss (dB/m) through trees in foliage exceeds predicted loss obtained from extrapolation of data from numerous sources at frequencies between 100 and 9000 MHz. These extrapolated values indicate only 1/3 to 1/10th the dB/m loss measured in the frequency range of 10 to 60 GHz. The term dB/m means dB loss per meter of measured foliage depth on a path, independent of the total path length. These studies have indicated a need to establish a method for determining depth of foliage. This aspect must be examined when comparing results.

b. Diffraction theory has a $\sqrt{f}$ dependence which sometimes is used to predict vegetation loss (dB/m) at higher frequencies. Although our results show that vegetation losses clearly increased (on the average) at these frequencies, the ratio was less than $\sqrt{f}$ over the 10 to 60 GHz frequency range. Normalized losses due to vegetation (dB/m) show a trend to decrease as the foliage path is lengthened which appears consistent with measurements at lower frequencies and with theoretical predictions.

c. The measured vegetation loss, in nearly all cases, as observed in Figure 2 was less at the 1 and 2 meter heights than at heights greater than 2 meters. This is the result of no leaves or sparse leaves at the 1 and 2 meter height and the general absence of underbrush on the sites used for these tests. Also, for trees and bushes, vegetation loss difference as a function of antenna polarization was very slight, whereas for tall grass, horizontal polarization clearly provides less loss. When comparisons of vegetation loss were made of deciduous groves, with and without foliage, the groves in summer foliage produced about 3 times as much loss in dB/m as the same groves in their defoliated state. Figure 3 shows an example of these observations.

d. An important factor is the dependence of received signal on spatial variance. Signal amplitude variations as large as 42 dB, see Figure 4, and typically 30 dB were observed for small displacements (≈ 25 cm) of the transmitter antennas in either the horizontal or vertical plane. There is considerable evidence that these deep fades are results of two relatively strong multipath signals adding destructively. Exposed (free of leaf cover) trunks and branches appear to be the source of the multipath.

e. Observations during windy periods (15 to 20 km/h) on a path with 10 or more meters of foliage depth produced signal variations (scintillations) of up to 15 dB with periods of less than 5 seconds. In addition, 8 dB fades of longer periods (1 to 5 minutes) were noted in gusting winds. The time series records in Figure 5, illustrate typical scintillations.

f. An increase in vegetation loss was noted during a rain on a single observation when water covered, or droplets formed, on leaves and branches

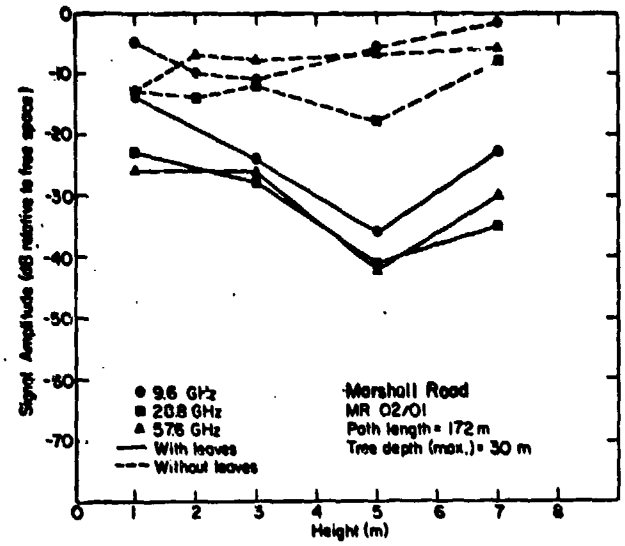

Fig. 3. Signal amplitude as a function of height for a cottonwood tree grove, with and without foliage (HH polarization).

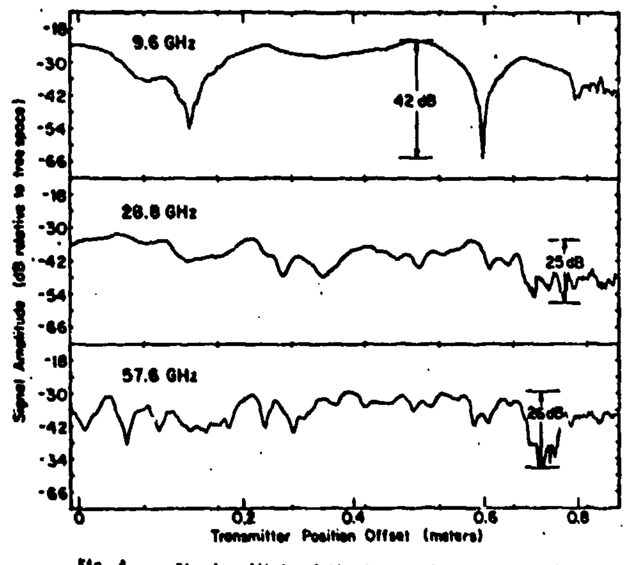

Fig. 4. Signal amplitude relative to transmitter antenna horizontal displacement. (MR01/01, path length = 152 m, height = 1 m, tree depth = 40 m, polarization = VV.)

of a willow tree. The signal loss increase was 3 to 5 dB at 9.6 GHz and 15 to 20 dB at 28.8 GHz; however, these maximum losses occured several minutes after the shower started, indicating perhaps a delay in wetting of leaves and branches contributing to propagation in sheltered regions. Moisture condensation prevented a measurement at 57.6 GHz. A wet snow fell during a conifer path observation and much of it stayed on the branches; however, no detectable signal change was noted.

g. Depolarization of signals propagated through exposed tree trunks showed less change than through leafy foliage where depolarized signal level increased by as much as 20 dB.

h. For a path with high loss due to foliage, a stronger received signal was observed when a common off-path volume (clear of tall trees) was illuminated. In the observed case a common scatterer, perhaps a bush or terrain feature in a clearing produced a side scatter signal level higher than the direct-path signal.

Additional data and a detailed discussion on these experiments can be found in a recent report [3].

3. Vegetation Theory

This theory treats vegetation (forests) as a random medium and uses a transport equation approach to analyze mm-wave propagation in this medium. The approach allows multiple scattering effects to be taken fully into account, while interference effects are neglected, a simplification which is justified by the experimental results; see Figure 4.

Transport theory splits the total field intensity into two components, the coherent (median) component and the incoherent (zero mean) component. While the coherent component possesses the same polarization properties as the incident field, the incoherent component is described by using a formulation in terms of the four Stokes' parameters. The theory thus leads to a system of four coupled integro-differential equations for the specific intensities of the incoherent component. However, by making reasonable assumptions concerning the statistical scattering characteristics of the forest medium, it is shown that for the first Stokes' parameter a single, uncoupled equation is obtained which is identical to the conventional scalar transport equation. The first Stokes' parameter is the quantity of primary interest since it is by definition the total intensity of radiation, i.e., it represents the sum of the intensities associated with two orthogonal polarizations.

The scalar transport equation has been solved for the case of a plane wave impinging upon the planar interface between an air half space and a forest half space characterized as a statistically homogeneous random

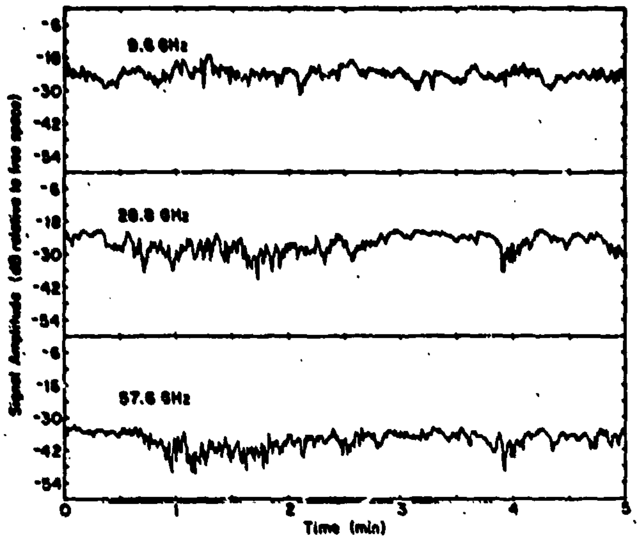

Fig. 5. Time series records of received signal amplitude during windy conditions.

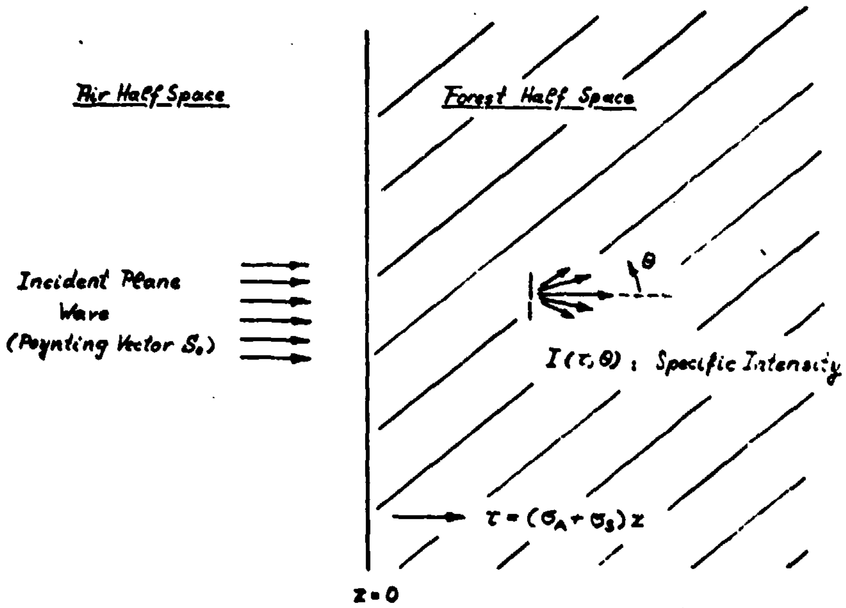

Fig. 6. Theoretical model: Plane wave normally incident upon planar interface separating air half space from statistically homogeneous random medium.

σ_A, σ_S : absorption and scatter cross section per unit volume.

$\tau = (\sigma_A + \sigma_S)z$: normalized distance into medium.

medium with an isotropic scatter function; see Figure 6. In the analysis of this model two approaches were taken:

a. A first order multiple scattering approximation (for small penetration depths) in conjunction with an asymptotic solution (for large penetration depths). This approach yields explicit expressions for the range dependence of both the coherent and incoherent field components, and for the directional spectrum of the incoherent component. Results are shown in Figures 7 and 8.

b. A rigorous method which represents the specific intensity by a series expansion in terms of Tschebyscheff polynomials. Computer evaluation of this theory has confirmed the trends indicated by the approximate theory and improved numerical accuracy.

The theory shows that at large penetration depths the forward scattered wave trains yield the major contribution to the received field intensity (Figure 7) and that the range dependency of this intensity is complex and not determined by a constant attenuation rate (Figure 8). A comparatively high attenuation rate at small penetration depth gradually reduces to a lower attenuation rate at larger distances.

A similar trend has also been observed at VHF and lower frequencies; but the underlying mechanism is completely different. While at VHF, the decreasing attenuation rate is due to the so-called up-over-down mechanism i.e., to the excitation of a low-attenuation lateral wave guided by the forest-to-air interface (Tamir theory), the effect at mm-waves is caused by the interaction of the coherent and incoherent field intensities: The coherent component dominates at small penetration depth but is attenuated due to both absorption and scatter, and therefore decreases rapidly. The incoherent component on the other hand scatters into itself and therefore decreases due to absorption only (though over an extended path). Hence this component, having a lower attenuation rate, will dominate at larger distances. At small distances of course the incoherent component is of low magnitude since it is generated by the scattering of the coherent component.

A rigorous theory using a scatter function with a strong forward component (and an omni-directional background) is presently being evaluated. Since in a forest environment all scatter objects are large compared to a mm-wavelength, strong forward scattering may be a more realistic assumption than the use of an isotropic scatter function.

4. Smoke and Dust Experiments

Field experiments on mm-wave propagation through smoke and dust were performed at Grafenwohr, West-Germany, during May-June 1979. Tactical

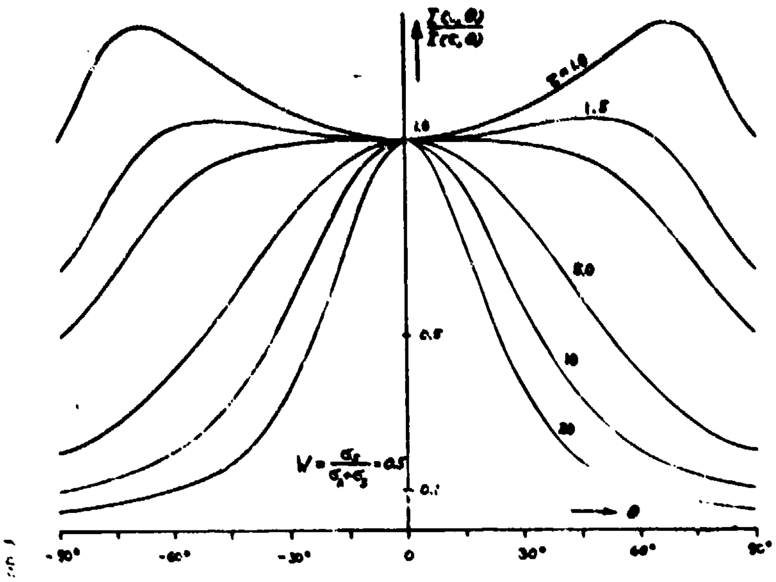

Fig. 7. Specific intensity I of incoherent component as function of θ for various τ and W = 0.5. Isotropic scattering assumed.

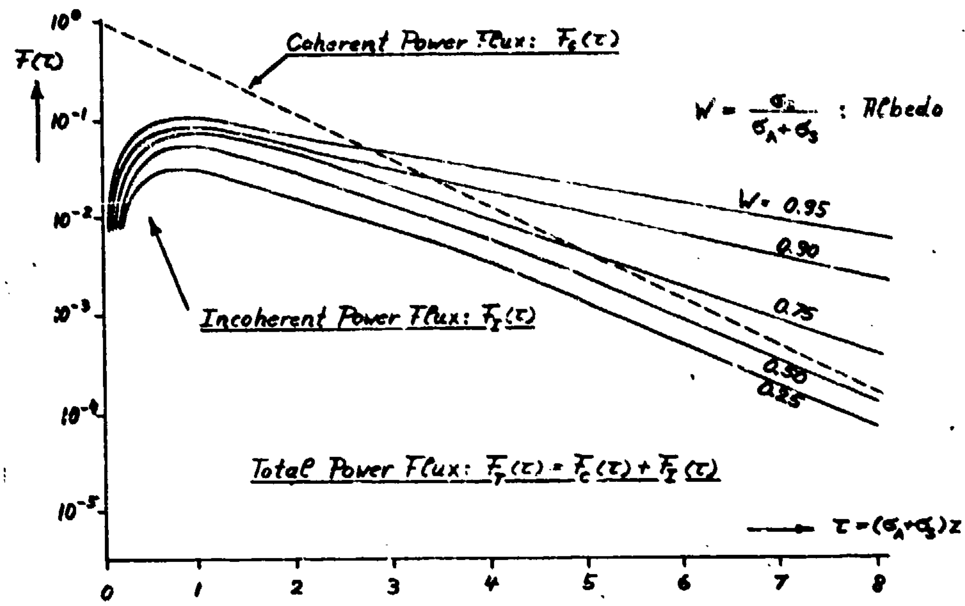

Fig. 8. Power flux in forward direction as function of τ. Isotropic scattering assumed.

$F_c(\tau)$: Magnitude of Poynting vector of coherent component;

$F_I(\tau)$: Forward flux of incoherent component.

radios developed by CENCOMS for the 38 GHz band were used in these tests. Characteristics of these radios are listed in Table 1; the data on 60 GHz radios is included in the table for use in Section 5.

Table 1
Millimeter Wave Radio Characteristics

Characteristics		38 GHz Radio	60 GHz Radio
Frequency		38.5 GHz	59.7 GHz
Transmit Power		50 mW	40 mW
Receiver Sensitivity			
Bandwidth (voice/video)		4/10 MHz	4/10 MHz
Beamwidth		5.5^o	3.0^o
Range	clear:	30/14 km	1.7/1.2 km
(voice/video)	15 mm/h rain:	5/3.5 km	1.3/0.95 km

The tests were conducted over a 2.75 km transmission path. In a first sequence of experiments an intense dust cloud was produced by an Armored Personnel Carrier driven parallel or perpendicular to the transmission path. A second test investigated propagation through a smoke (labeled HC) derived from tetrachlorine and zinc powder. A third experiment was performed over a shorter path of 500 m length and tested a smoke provided by German technicians; its chemical composition was not revealed.

Measured data show that HC smoke or a cloud of dust having an extension of several hunderd meters will cause an attenuation of less than 0.3 dB. The smoke used in the third test was slightly less transparent; but attenuation remained below 1 dB. The experiments thus confirm the effectiveness of mm-wave beams in penetrating through dust and smoke.

5. Dirt III Experiments

The Dirt III experiments were conducted at Ft Polk, Louisiana, during April 1980. CENCOMS participated in these experiments to investigate the effect of dust and debris clouds, produced by artillery shell detonations, on the performance of mm-wave communication links. Two such links, operating at 38 GHz and 60 GHz, respectively, were studied using the radios of Table 1. The radios were tripod-mounted i.e., at a height of $\sim$1.5 m above ground. The transmission path had a length of approximately 850 m. At this distance the (clear air) fade margin was 25 dB for the 38 GHz radios and 9 dB for the 60 GHz link.

The testing consisted in measuring received power (or AGC) as a function of time after detonation of artillery shells that were placed either directly below the line-of-sight (LOS) or at a lateral distance of 10 m or 20 m off the LOS. The munitions were either buried or placed on the ground. The distances of the detonation site from the two terminals of each link were approximately 600 m and 250 m. Both Russian and American artillery rounds were used. The sizes of the rounds were 122 mm and 152 mm for the Russian and 105 mm and 155 mm for the American munitions. Figure 10 shows a timesequence of the dirt and debris cloud of a typical surface detonation.

As an example of measured data, Figure 9 shows a stripchart recording of the AGC output of the 38 GHz and 60 GHz radios in response to a 122 mm, buried, on-axis detonation. Note that the time coordinate increases from right to left. On the recording, attenuation levels of 1, 3, 6 and 10 dB are indicated. In Table 2, the amount of time during which the attenuation was greater than these levels is listed for the 38 GHz radios and for the (worst) case of on-axis detonations. It is apparent that signal strength recovers to nearly normal levels within a few seconds. Similar tables were compiled for off-axis explosions and for the 60 GHz link.

Table 2

Effect of on-axis detonation cloud on signal transmission at 38 GHz:

Maximum attenuation A_{max}, and time t_n for which attenuation exceeded n dB

Shell size (mm)	Placement (B: buried, S: surface)	A_{max} (dB)	t_{10} (seconds)	t_6 (seconds)	t_3 (seconds)	t_1 (seconds)
122	S	10.5	0.12	0.25	1.00	1.50
105	S	5.8	—	—	0.78	3.4
152	S	20.0	0.25	0.94	1.56	4.38
155	B	22.1	0.16	0.94	1.56	8.13
122	B	21.5	0.31	0.63	0.78	4.06

Also shown in Table 2 is the maximum attenuation A_{max} occuring immediately after the detonation. For the 38 GHz radios this attenuation remained within the fade margin of 25 dB so that communication could be maintained at all times. For the 60 GHz radios, on the other hand, A_{max} exceeded the fade margin of 9 dB in several instances (of on-axis detonations) and communication was temperarily interrupted. Outage times howevear remained below 1 second. For off-axis explosions at distances of 10 m and 20 m from the LOS, the maximum attenuation did not exceed 6 dB and 3 dB respectively, and no outages occured at either frequency. It can thus be stated the the effect of artillery shell detonation clouds on mm-wave communication is minimal. As a general rule, such effects will decrease further with increasing link length.

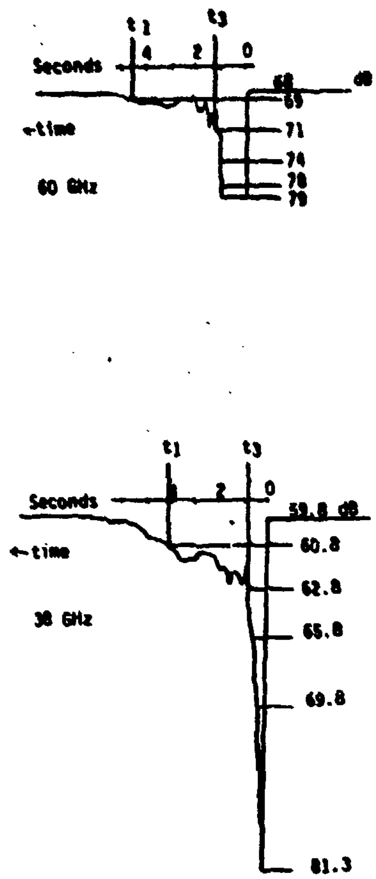

Fig. 9. Stripchart recording of 122 mm, buried, on-axis event: Attenuation vs. time

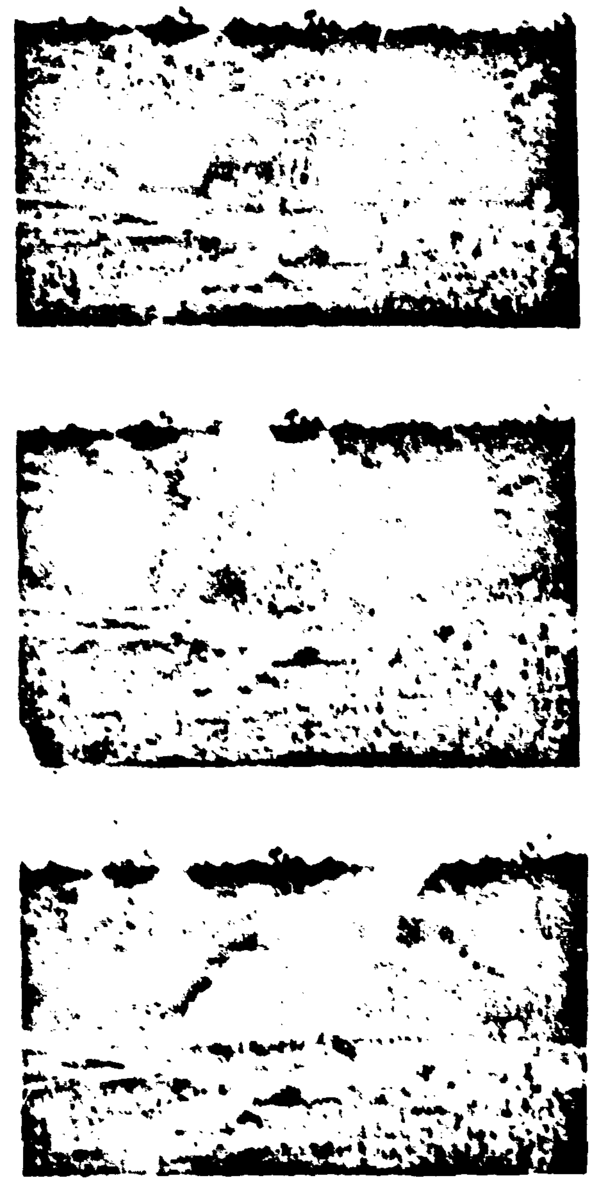

Fig. 10. Typical time sequence of detonation cloud

As a consistent trend it was observed that, in the case of on-axis detonations, buried shells produced stronger attenuation than munitions exploded on the surface, while for off-axis detonations the situation was reversed. This is easily explained by the fact that buried detonation tend to expell particulate matter in the vertical direction thus producing a more collimated explosion cloud than surface explosions which generate laterally more extended clouds. Collimation of the explosion cloud also explains an effect observed for on-axis detonations, that a second, smaller attenuation maximum occurs approximately 4 seconds after a buried explosion. This attenuation peak is attributed to the heavier pieces of dirt and debris thrown almost vertically into the air and passing the vicinity of the LOS a second time while falling back to the ground. In general the experiments show that strong mm-wave attenuation, as it occurs immediately after the detonation, is caused by the larger and heavier particulate matter which however remains airborne for a short time span only. Lighter particles, which remain suspended in the air for a longer period of time, have negligible effect on mm-wave transmission as evidenced by the smoke and dust experiments reported in Section 4.

A detailed discussion of the Dirt III mm-wave experiments can be found in a recent report [4], which also presents an analytical approach allowing generalization of experimental results to other geometrical situations. The analysis is based on a description of the size of the explosion cloud and its distance from the LOS in terms of the Fresnel zones of the radio link in the plane (normal to the LOS) where the detonation cloud has its center.

6. Conclusions

Experimental investigations supported by theoretical studies confirm that mm-wave links are capable of providing highly reliable communication in the battlefield environment. Specifically

a. Millimeter wave transmission through a line of trees or placement of radios at moderate depths into woods (for camouflage purposes) will be possible, although at the price of a reduced transmission distance. The range reduction well depend on vegetation depth and density.

b. Millimeter wave attenuation by smoke and dust is minimal and not likely to noticeably affect link availability.

c. Artillery shell detonations may temporarily interrupt signal transmission but only under unfavorable circumstances, i.e., if the explosion occurs below ground and the detonation cloud intercepts the line-of-sight. Even under these conditions, outage times will be less than 1 second.

These results apply to voice, video as well as data transmission.

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